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Procedia CIRP 26 (2015) 373 – 378

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12th Global Conference on Sustainable Manufacturing

Scenarios in multi-objective optimisation of process parameters for sustainable machining

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Abstract

Sustainable machining needs to consider multiple objectives for fulfilling environmental and economic requirements. Pareto front usually employed to present multi-objective optimisation results. However, the Pareto fronts are difficult to understand and inefficient when there are more than 2 objectives. This problem is addressed in this paper, by enumerating and characterising all the 128 scenarios in sustainable machining operation involving 7 objectives including energy, cost, time, power, cutting force, tool life and surface finish. Results show that all the scenarios can be converted to single-objective situation which has a unique solution or a set of conflicting bi -objective cases which can be represented as a single Pareto front.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.

Keywords: Energy minimisation, multi-objective machining optimisation, problems and solutions scenarios, sustainable machining

1. Introduction

At present, sustainable machining process has been widely demanded by manufacturing industry to address the financial pressure from increasing energy price and the political pressure from legislation on reduction of environmental impact. Research contributions [1-3] have proposed several methods to minimise the energy consumption in the machining process by using single-objective optimisation techniques. However, a sustainable machining process needs to consider multiple objectives for fulfilling environmental and economic requirements. Unfortunately, existing machining optimisation methods are limited in their abilities when multiple objectives need to be considered. The optimal results achieved are not holistic and may contain biases and assumptions. Also, the optimising process is not efficient and difficult to understand.

To address this issue, a systematic methodology is proposed in this paper for solving multiple-objective machining optimisation problems when sustainability factors such as energy consumption are considered.

1.1. Issues for optimisation of machining sustainability

The observations from literatures show that the major issues of machining sustainability optimisation are:

- Most of the current research contributions only considered 2 or 3 selected objectives at same time. So the optimal solutions achieved from these research contributions are more like case studies which cannot provide a generic methodology to solve general multi-objective machining optimisation problems.
- The existing multi-objective optimisation approaches have limitations when they are applied in machining optimisation. The optimal results achieved may contain biases and assumptions. The optimising process is difficult to understand and not efficient when there are more than 2 objectives need to be considered.
- Characteristics of machining optimisation when energy is considered as an additional objectives are still not clear. So the optimal results of sustainability obtained are insufficient and not in a position to represent the practical requirements.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.
doi:10.1016/j.procir.2014.07.186

1.2. Research aim and objectives

To address the above issues for sustainable machining, the aim of this paper is to develop a systematic methodology which can provide holistic solutions and improve the efficiency for multiple-objective machining optimisation problems.

To achieve the aim set, a Problem-Solution-Scenario approach will be proposed and introduced in the following section. The design of problem scenario will be described in section 2 to create a problem domain for decision makers to better understand what the problems/requirements they have. The result analysis for multi-objective problems will be introduced in section 3. The case studies for each scenario will be presented to demonstrate the performance of the proposed methodology. The design of solution scenario will be presented in section 4. The solution domain will be created by analysing optimal solutions of problem scenario which allows decision makers to get the optimal solutions based on the problems they have. A review of related research will be presented in section 1.3 to clearly introduce the development of machining optimisation and identify the gaps of knowledge.

1.3. Related research of multi-objective machining optimisation

The purpose of multi-objective optimisation (MOO) is to assist decision makers select the optimal plan or make a better decision. Marler and Arora [4] conducted a survey of current nonlinear multi-objective optimisation methods for engineering use. They reported that the current methods can be divided into three major categories based on the preference type of decision maker, which is priori articulation, posteriori articulation and no articulation. They also claimed that no single approach is superior. The selection of optimisation method must depend on the type of information provided, the decision maker's preferences, the solution requirements and the availability of software.

For the implementation in machining optimisation, the MOO methods can be divided into two categories based on the techniques applied which are Priori techniques and Posterior techniques (because the optimisation methods applied for solving no articulation of preferences problems are just simplification of Priori techniques [4]). The basic principle of priori techniques is to convert MOO problems to single-objective optimisation by combining different objectives functions as a single objective function. The optimal result will be displayed as a unique solution. On the other hand, posterior techniques (such as evolutional computing techniques) will present a set of feasible solutions for decision to choose. This set of feasible solutions is called Pareto optimal set and can be represented as Pareto front.

For using priori techniques, Malakooti et al. [5] proposed a method for assessing the weights of the importance of different criteria on machinability include production rate, operation cost, product quality, tool life, surface roughness, accuracy, temperature, power/force/torque, vibration and noise. A machinability function was developed which can combine different process outputs together. The weights of the importance with the respect of these attributes can be calculated and evaluated according to decision maker's preference. Based on this method, Cus and Balic [6] optimised cutting speed and feed rate by using genetic algorithm. A unique optimal plan was achieved for end milling operation with the consideration of production rate, operation cost and surface roughness. The work was extended in Cus and Zuper's further publications [7-9] by using different optimisation methods for turning and end milling operation. Tolouei-Rad and Bidhendi [10] investigated optimisation of machining parameters for conventional milling operation. Profit rate was utilised to combine machining cost and process time. A case study of machining a multiple-feature component showed that up to 350% improvement can be achieved from handbook recommendations.

On using posteriori techniques, Sardinas et al. [11] used genetic algorithm to optimise production rate and cost for turning operation. Pareto front was used to represent the feasible optimal results. Kapat and Ozel [12] used neural network and particle swam algorithm to optimise three conflicting cases: surface roughness and productivity, material removal rate and tool life, and surface roughness and surface residual stress. Three sets of Pareto fronts were plotted to show the optimal results for each case. Pareto fronts were also used to show the optimal results of two conflicting objectives such as surface roughness and tool wear by Roy and Mehnen [13], and material removal rate and tool wear by Yang and Natarajan [14] for turning operation.

For optimising machining operation with energy consideration, Sheng and Srinivasan [15] developed an environmentally conscious multi-objective process planning method, which was beyond the traditional methods that just considered economic criteria. This new process planning method estimated the process mechanics, tool life, fluid flow, process energy, machining time and the mass flow of component waste streams. These waste streams can be weighted by environmental factors such as toxicity, carcinogenicity, irritation, reactivity and flammability. Thus the process and parameter can be selected based on objectives including process energy, process time, surface finish and weighted mass flow. Mativenga and Rajemi [16] carried out a research to optimise energy consumption for turning operation. They also reported that the optimal cost can be achieved with optimal energy by using the identical optimal process parameters. Similar finding has also been reported in Authors' previous work [3]. Avram et al. [17] proposed a multi-criteria decision-making approach. Criteria rating scale values are specifically set based on degree of decision maker's preferences. Then the overall performance of different process plans/cutting strategies can be calculated and selected with the corresponding requirements.

1.4. Summary of gaps from literature

The sustainability awareness in manufacturing/machining processes such as energy consideration brings new requirements for existing multi-objective machining optimisation research. In carrying out the review of current research contributions, the following issues/problems can be identified:

- For priori techniques, decision maker's preferences are required to determine the weight for each objective or directly combine the objectives together. However, priori techniques are not suitable for the cases that the decision makers' preferences are not clear, or the optimising objectives are not able to be reasonably combined.
- For posteriori techniques, Pareto front is usually employed to present the optimal results for the problems when two conflicting objectives need to be considered. However, when there are more than 2 objectives, multiple Pareto fronts are required to present the optimal results for every two objectives. These multiple Pareto fronts are difficult to understand, and analysis process is complex and inefficient.
- Most multi-objective machining optimisation research with energy consideration reviewed only used priori techniques. The optimal results achieved by using these methods are a unique optimal plan, but not a set of feasible solutions. So, it is necessary to investigate the optimal solutions of multi-objective machining optimisation with energy consideration by using posteriori techniques.

2. Problem Scenarios in Multi-objective Machining Optimisation

2.1. Overview of problem scenario

To accurately describe the problems of machining optimisation, the design of problem scenario will be introduced in this section. The concept of problem scenarios is developed based on the cases of machining optimisation. Each case represents a combination of considered objectives. These scenarios can be considered as the problem domain which allows decision makers to select the corresponding scenario based on their requirements.

For n objectives, the total number of problem scenarios Ns can be identified by using Equation 1. Where i is the number of objectives considered.

$$N_s = C_n^0 + C_n^1 + \cdots + C_n^i + \cdots + C_n^n \quad (1)$$

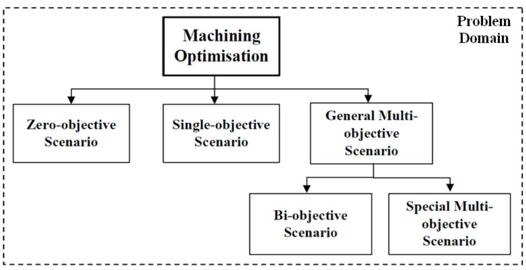

Fig. 1. Classification of Problem Scenarios

The example shown in this paper is to investigate end milling operation with the consideration of the 7 objectives: energy, cost, time, power, cutting force, tool life and surface finish. By enumerating the combination of objectives, 128 scenarios in sustainable machining optimisation can be generated and classified in 3 major scenarios in Fig. 1. The explanation of each scenario will be introduced in the following section.

2.2. Zero-objective and Single-objective scenarios

The definition of zero-objective scenario is that the decision makers have no idea about how to improve their machining process or they only have some constraints. In this case, there is only 1 ($C_7^0 = 1$) scenario in zero-objective scenario. The solution of zero-objective scenario is to describe the problem of machining optimisation and uncover the potential possibility of the current process. The result can be demonstrated by using a non-constrained contour plot to show the states of optimal criterions.

Fig. 2(a) indicates the solution of zero-objective scenario with energy, cutting force and surface roughness considerations. It clearly describes the optimisation problem and presents the characterisation of each criterion. So the decision makers can continue to refine their requirements, determine the optimal objectives and select the satisfied machining plan according to the presented contour plot.

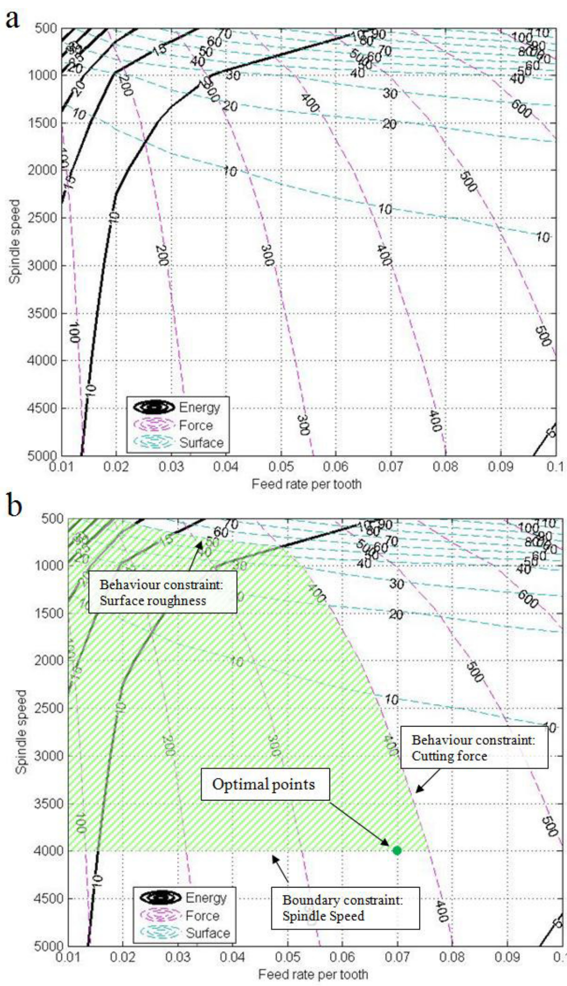

Fig. 2. Solution of (a) zero-objective scenario; (b) single-objective scenario.

The definition of single-objective is that only one objective function is considered for an optimisation problem. It refers to the practical situations that when decision makers have very clear target/aim/objective to improve their process based on one specific criterion. The main task in this scenario is to correctly define the constraints to reduce the search space and locate the optimum value. In this case, there are 7 ($C_7^1 = 7$) scenarios in single-objective scenario. The result can be also demonstrated by a contour plot of the optimal objective. A feasible search space can be indicated with the consideration of constraints. Fig. 2(b) indicates the solution of energy minimisation with constraints of cutting force ($\leq 400N$), surface roughness ($\leq 0.05mm$) and spindle speed ($\leq 4000rpm$). The green area represents the constrained feasible region of search space, and the unique optimal result can be determined.

2.3. Multi-objective scenario

Generally, multi-objective scenario contains the scenario which involves more than one objective function to be optimised simultaneously. According to the number of objectives, general multi-objective scenario can be further divided into two sub-scenarios: bi-objective scenario and special multi-objective scenario.

The definition of bi-objective scenario is that two objectives will be considered in machining optimisation simultaneously. There are 21 ($C_7^2 = 21$) scenarios in bi-objective scenario. The solutions of bi-objective scenario can be represented as a single Pareto front.

The definition of special multi-objective scenario is that more than two objectives will be considered in machining optimisation simultaneously. There are 99 ($C_7^3 + C_7^4 + C_7^5 + C_7^6 + C_7^7 = 99$) scenarios in this sub-scenario. The solutions of special multi-objective scenario are usually complex and require multiple Pareto fronts. The more objectives need to be considered, the more complex the solution will be.The specific analysis will be carried out in the following section.

3. Result Analysis for Multi-objective Scenario

3.1. Pareto front for Bi-objective scenario

Fig. 3(a) to 3(f) show the Pareto fronts of energy consumption with cost, surface roughness, tool life, cutting force, time and power requirement. From the Pareto fronts presented, the optimal result for bi-objective scenario can be classified into two categories: non-conflicting and conflicting.

For the scenarios in non-conflicting bi-objective category, such as energy and cost/time, the optimal solution will be a unique optimal point. Actually, this type of multi-objective optimisation problems can be converted to a single-objective optimisation problem, and solved by using single-objective optimisation algorithms.

For the scenarios in conflicting bi-objective category, such as energy to surface roughness, tool life, cutting force and power, the optimal solutions of this category will be a Pareto front which contains a set of feasible solutions without additional preferences. According to the plotted Pareto front, decision makers can evaluate their current machining plans and make the suitable adjustment based on their preferences.

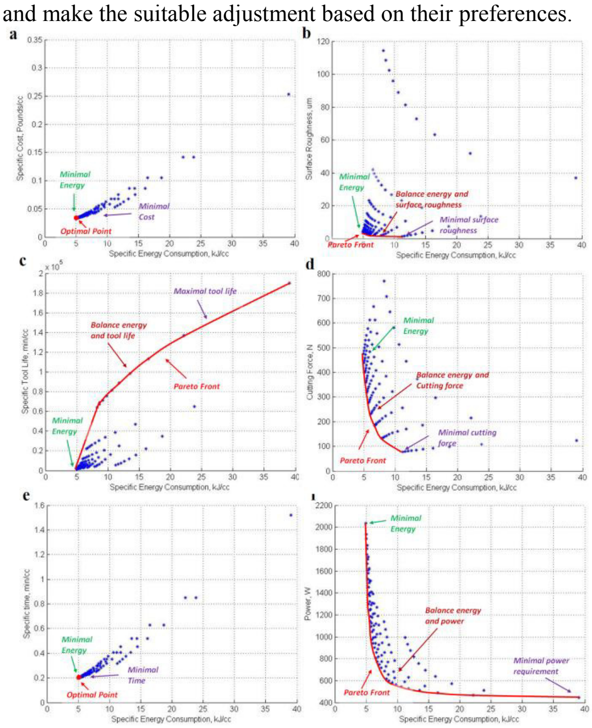

Fig. 3. Pareto front of energy to (a) cost; (b) surface roughness; (c) tool life; (d) cutting force; (e) time; (f) power.

3.2. Optimal solution for special multi-objective scenario

Normally, Pareto front is utilised to solve two conflicting objectives optimisation problems. However, Pareto fronts are difficult to understand and inefficient when there are more than 2 objectives need to be considered. For example, if 5 objectives need to be considered, there are 10 ($C_5^2 = 10$) Pareto fronts should be plotted to show the relationship between each pair of objectives. The analysis process will be very complex which requires lots of explanation, and the optimal solution is very difficult to be clearly presented.

However, according to the characterisation of machining optimisation, the objectives are monotonously increasing or decreasing with the increase of process parameters. Because every pair of non-conflicting objectives can be considered as a single-objective problem, it can be easily inferred that all the non-conflicting special multi-objective scenarios can converted to a single objective optimisation.

Based on the above conclusion, the optimal solution for special multi-objective scenario can be simplified by carrying out an analysis and combining process with the steps below:

- Characterise the optimising objectives. Identify the relationship between each pair of objectives (Are they conflicting or not conflicting?).
- Combine the non-conflicting objectives. The multiple non-conflicting objectives can be combined by using one representative objective (could be anyone of them).
- Evaluate the remaining representative objectives. If only one objective remains, then the problem can be classified

to non-conflicting category. Otherwise it can be classified to conflicting category. The classification and solutions for special multi-objective scenario are the same as bi-objective scenario. So the multi-objective scenario can be generally classified into two categories.

Fig. 4 shows the analysis process of general multi-objective machining optimisation. It is obvious that the optimal result will be a unique optimal solution if all the objectives are not conflicting with each other. It means the optimal solution of non-conflicting category is the same as the solution of single-objective scenario. The optimal result of conflicting category will be a unique Pareto front which is the same as bi-objective conflicting cases shown in Fig. 3.

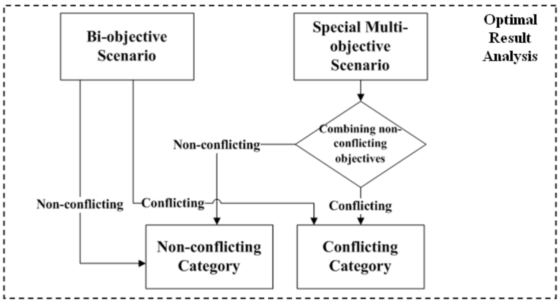

Fig. 4. Result analysis process of multi-objective machining optimisation

An example has been conducted to demonstrate the process of how to use the proposed method to optimise 4 conflicting objectives energy, cost, cutting force and surface roughness. By analysing the Pareto fronts of each pair of objectives, energy and cost are not conflicting, cutting force and surface roughness are not conflicting. So they can be respectively combined and represented by energy and cutting force. Then the optimal result can be plotted as a unique Pareto front shown in Fig. 5. From the figure, decision makers can also easily evaluate their current machining plans and make the suitable adjustment based on their preferences.

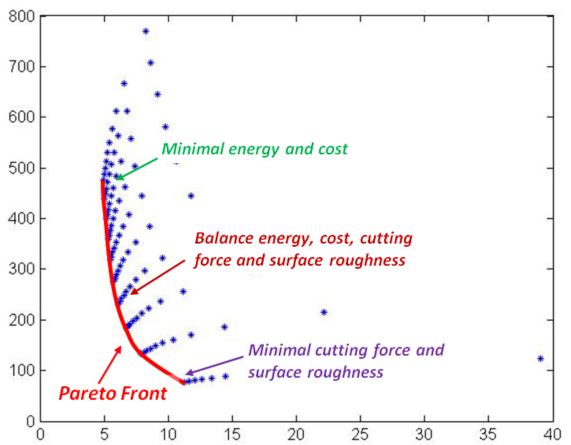

Fig. 5. Unique Pareto front for optimising 4 objectives: energy, cost, cutting force and surface roughness

4. Classification of Solution Scenario

According to the analysis of optimal results for each problem scenario, the optimal solutions for machining optimisation can be classified into 3 scenarios, which are:

- **Descriptive scenario**. The solutions in this scenario are to address the problems in zero-objective scenario. The functions of these solutions are to comprehensively describe the problems of machining optimisation for decision makers who do not have explicit optimising objectives, and help them to uncover the potential improvement of their current machining processes. Usually, the solutions in this scenario will be represented as a non-constrained contour plot.
- **Unique solution scenario**. The solutions in this scenario are to address the problems in single-objective scenario and non-conflicting category of multi-objective scenario. The optimising process for this solution scenario can be conducted by using any existing single optimisation algorithms. The solutions in this scenario are a unique optimal solution/result for the problems and can be represented as a constrained contour plot.
- **Pareto front scenario**. The solutions in this scenario are to address the problems in conflicting category of multi-objective scenario. The optimal results in this scenario are not a unique optimal result but a set of feasible solutions. The optimal solutions in this scenario can be represented by as a single Pareto front.

The proposed solution scenarios in this section can be consisted together as a solution domain which will provide the corresponding optimal solution for the scenarios in the problem domain. Fig. 6 shows the structure of proposed scenario-based framework for machining optimisation. This framework clearly introduces how to solve machining optimisation problem. It is especially suitable for multi-objective problems, and provides a generic method to address the issues for achieving a sustainable machining process.

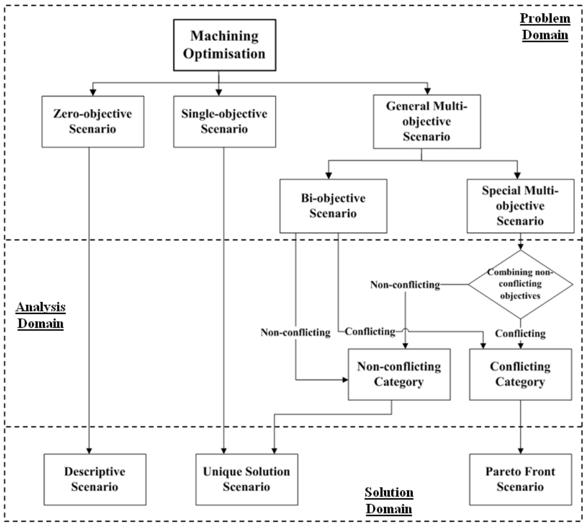

Fig. 6. Scenario-based framework for machining optimisation

5. Conclusion and Further Work

In this paper, a scenario-based systematic methodology was developed and reported to provide a comprehensive solution for decision makers to solve machining optimisation problems with sustainability considerations. To address the issues raised from current research contributions and achieve the objectives set in section 1.2 the following tasks have been completed:

- The problem scenarios have been developed to describe the actual problems of machining optimisation. By enumerating and characterising the problems in sustainable machining operation involving 7 objectives including energy, cost, time, power, cutting force, tool life and surface finish, 128 scenarios can be identified and classified into 3 major problem scenarios: zero-objective, single-objective and general multi-objective scenarios based on the number of objectives considered. Based on the complexity of optimal results (number of Pareto fronts required), the general multi-objective scenarios can be further divided into 2 sub-scenarios: bi-objective and special objective scenario (optimal objectives more than 2).
- The solutions for multi-objective scenarios have been investigated by characterising of Pareto fronts of bi-objective sub-scenarios. Based on the analysis, the multiple objectives can be divided into two categories: non-conflicting and conflicting category. Non-conflicting multi-objective problems can be converted to single-objective situation which has a unique solution, and conflicting multi-objective problems can be converted to a set of conflicting bi-objective cases which can be represented as a single Pareto front.
- According to the analysis of optimal results, the solutions for machining optimisation can be classified into 3 solution scenarios which are descriptive scenario (for zero-objective scenario), unique solution scenario (for single-objective scenario and non-conflicting category of multi-objective scenario) and Pareto front scenario (for conflicting category of multi-objective scenario). The proposed solution scenarios can be consisted together as a solution domain to provide an optimal solution for the corresponding problem scenarios.
- Based on the above results, a scenario-based framework has been proposed for solving general machining optimisation. It can provide a generic and systematic methodology for decision makers to better understand their machining processes and address recent challenges from sustainable requirements.

The research contributions reported in this paper can be further developed and implemented in the following aspects:

- The proposed scenario-based framework can be further extended to a generic optimisation framework by combining with modelling techniques, optimisation algorithms and solution database.
- The results can be used to develop a "How to" toolkit (such as handbook, manual, simple computer software, smart phone applications, etc.) which can be easily implemented in a practical manufacturing process.
- The results can be integrated into next general CAM/CAPP system.

Acknowledgements

This work is funded by University of Greenwich. The authors are grateful to Dr. Andrew Adekunle for his kind support during the preparation of the paper and suggestions for results represented. Also, the authors really appreciate the patience, understanding and support of the conference committee.

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